SUPER-JUNCTION SEMICONDUCTOR DEVICE

FIELD OF THE INVENTION

The present invention relates to semiconductor devices such as MOSFET's (insulated gate field effect transistors), IGBT's (insulated gate bipolar transistors), bipolar transistors and diodes having a vertical semiconductor structure including an alternating conductivity type layer that provides a current path in the ON state of the devices and is depleted in the OFF state of the devices.

BACKGROUND

A semiconductor device may be roughly classified as a lateral semiconductor device that arranges its electrodes on a major surface or a vertical semiconductor device that distributes its electrodes on both major surfaces facing opposite to each other. When the vertical semiconductor device is ON, a drift current flows in the thickness direction of the semiconductor chip (vertical direction). When the vertical semiconductor device is OFF, the depletion layers caused by application of a reverse bias voltage expands in the vertical direction. In order to provide a vertical semiconductor device with a high breakdown voltage, in that the current flows between the opposite-facing electrodes on the major surfaces, it is necessary to increase the specific resistance of the highly resistive layer between the opposite-facing electrodes and to thicken the highly resistive layer.

FIG. 10 shows a perspective cross sectional view of a conventional vertical MOSFET as an example of a power device. Referring now to FIG. 10, the vertical MOSFET includes a highly resistive n-type drift layer 2, p-type well regions 3 in the surface portion of n-type drift layer 2, and n$^+$-type source regions 4 in p-type well regions 3. Trenches 9 are dug from the surfaces of n$^+$-type source regions 4 down to n-type drift layer 2. A gate electrode 6 is buried in trench 9 with a gate insulation film 5 interposed therebetween. A source electrode contacts with p-type well regions 3 and n$^+$-type source regions 4. A drain electrode contacts with a drain layer 1.

In the vertical semiconductor device as shown in FIG. 10, highly resistive n-type drift layer 2 works as a region for making a drift current flow vertically when the MOSFET is in the ON-state. In the OFF-state of the MOSFET, depletion layers expand from the pn-junctions between p-type well regions 3 and n-type drift layer 2 into n-type drift layer 2, resulting in a high breakdown voltage of the MOSFET. Thinning highly resistive n-type drift layer 2 (shortening the current path in highly resistive n-type drift layer 2) is effective for substantially reducing the on-resistance (resistance between the drain and the source) of the MOSFET, since the drift resistance is lowered in the ON-state of the device. However, the short current path in n-type drift layer 2 causes breakdown at a low voltage and the breakdown voltage (the voltage between the source and the drain) is lowered, since the expansion widths of the depletion layers expanding from the pn-junctions between p-type well regions 3 and n-type drift layer 2 are narrowed and the electric field strength in the depletion layers soon reaches the maximum (critical) value for silicon. However, in the semiconductor device with a high breakdown voltage, a thick n-type drift layer 2 inevitably causes high on-resistance and loss increase. In short, there exists a tradeoff relation between the on-resistance (current capacity) and the breakdown voltage of the MOSFET. The

breakdown voltage is sustained by the depletion layers expanding from the pn-junctions between p-type well regions 3 and n-type drift layer 2. The breakdown voltage increases as the impurity concentration in n-type drift layer 2 is lower and n-type drift layer 2 is thicker.

The on-resistance $R_{ON}A$ and the breakdown voltage V_B of the vertical MOSFET are related with each other by the following relational expression (1) (cf. Hu. C., Rec. Power Electronics Specialists Conf., San Diego, (1979), p 385).

$$R_{ON}A = (27/8)(V_B^2/\mu \in E_C^3) \tag{1}$$

Here, μ is electron mobility, $\in$ is dielectric permeability of a semiconductor, and E_C a maximum electric filed strength. The on-resistance $R_{ON}A$ is proportional to the square of the breakdown voltage V_B and increases quickly with increase of the breakdown voltage V_B.

Increase of the on-resistance with increase of the breakdown voltage poses a serious problem not only on the MOSFET's but also on the power devices, including a drift layer and exhibiting a high breakdown voltage, such as IGBT's, bipolar transistors and diodes. Recently, a new junction structure has been proposed to obviate the problem described above (cf. G. Deboy et al., "A new generation of high voltage MOSFETs breaks the limit line of silicon", Technical digest of IEDM '98 (1998), pp. 683–685, European Patent 0 053 854, U.S. Pat. No. 5,216,275, U.S. Pat. No. 5,438,215, and Japanese Unexamined Laid Open Patent Application H09(1997)-266311). The proposed semiconductor devices include an alternating conductivity type drift layer formed of heavily doped n-type regions and p-type regions alternately laminated with each other. The alternating conductivity type drift layer provides a current path in the ON-state of the device and is depleted to bear the breakdown voltage in the OFF-state of the device.

Hereinafter, the semiconductor device including an alternating conductivity type drift layer will be referred to as the "semiconductor device with a super-junction structure" or as the "super-junction semiconductor device".

FIG. 11 is a perspective cross sectional view of a vertical MOSFET having a super-junction structure. Referring now to FIG. 11, the vertical MOSFET of FIG. 11 is different from the vertical MOSFET of FIG. 10 in that the vertical MOSFET of FIG. 11 includes a drift layer 12, that is not a single-layered one but formed of n-type drift regions 12a and p-type partition regions 12b alternately laminated with each other. In the figure, p-type well regions 13, n$^+$-type source regions 14, gate insulation films 15, and gate electrodes 16 are shown. A source electrode contacts with p-type well regions 13 and n$^+$-type source regions 14. A drain electrode contacts with a drain layer 11.

In the structure shown in FIG. 11, the on-resistance $R_{ON}A$ and the breakdown voltage V_B of the vertical MOSFET are related with each other by the following relational expression (2) (cf. T. Fujihira "Theory of Semiconductor Super-junction Devices" Jpn. J. Appl. Phys. Vol. 36 (1997), pp. 6254–6262).

$$R_{ON}A = 4d(V_B/\mu E_C^2) \tag{2}$$

Here, d is the width of n-type drift region 12a.

As the relational expression (2) indicates, the on-resistance $R_{ON}A$ of the super-junction semiconductor device increases in proportion to the breakdown voltage V_B and more slowly than in the conventional semiconductor structure, the on-resistance $R_{ON}A$ thereof is related with the breakdown voltage V_B by the relational expression (1).

FIG. 12 is a graph relating the breakdown voltage and the on-resistance for the super-junction semiconductor devices.